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The views, opinions and/or findings contained in this report are those of the author(s) and should not be construed as an official Department of the Army position, policy or decision, unless so designated by other documentation.

12 a. DISTRIBUTION / AVAILABILITY STATEMENT

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12 b. DISTRIBUTION CODE

13. ABSTRACT (Maximum 200 words) During the period 6/15/98-6/14/01, a theory for utilizing Lie Algebraic formulations to enable constraint stabilization was developed. Subsequent refinements of the theory has lead to significant progress in 1) switching stability of models for barrel simulation and 2) stabilization of constraint violation in simulations of military ground vehicles. Following these lines, the research team developed of a theory for reduced order models for flexible components in multibody vehicles. Essentially, rapid retargeting of weapons subsystems mounted on military vehicles require extraordinary care in developing reduced order models for control system design and simulation. Conventional flexible component representations employ global Ritz vectors, or component modes, to achieve order reduction. The complexity induced in the coupled rigid-flexible multibody representations is considerable in these formulations. The methodology developed within this research effort employs an adaptive mode switching technique. In this formulation, a very small number of component modes are adaptively selected from a highly redundant dictionary of component modes. Preliminary computational and numerical experiments indicate that the method is very promising for obtaining accurate, low dimensional models of system dynamics. From a technical standpoint, the research team has established conditions that guarantees that the modal selection process yields a stable numerical scheme. In addition to the work deriving the adaptive modal scheduling technique for dynamic simulations, the research team has worked consistently to maintain strong connections to Army laboratories. During August, 1998 the principal investigator visited Picatinny Arsenal and initiated collaborations with Michael Mattice to develop nonlinear simulation and experimental verification in the context of virtual prototyping. Preliminary designs for an experimental testbed to simulate nonlinear dynamics of vehicle mounted, rapid-retargetting weapons platforms were developed. The co-principal investigator for this project has coordinated efforts with Dr. Mike Hale at Redstone Technical Test Center to employ their proprietary HUMV models for simulation and vehicle virtual prototyping. During Novermber, 1999, the rincipal investigator met with Michael Mattice of Picatinny Arsenal and Dr. William Clark at the University of Pittsburgh to develop esearch strategies to achieve virtual prototyping of the HMMWV. Mike Mattice of Picatinny arsenal and Dr. Clark have provided their models and documentation of the CLAWS weapon platform. The technical content of the formulations has been published in two prestigious peer-reviewed journals, *Philosophical Transactions, Royal Society of London A* and *Nonlinear Dynamics*. This work was disseminated to the research community in two conference presentations held at the *41st Structures, Structural Dynamics and Materials Conference* held in April, 2000, Atlanta.

14. SUBJECT TERMS

nonlinear multibody dynamics, nonlinear control ,lie algebraic control, vehicle simulation

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Nonlinear Dynamic Simulation and Control of Military Ground Vehicles

A Final Report for Project
P-38768-EG

For the Period
6-15-98 – 6/14/01

Submitted to

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November 27, 2001

This report summarizes the final status of the project entitled

"Nonlinear Dynamic Simulation and Control of Military Ground Vehicles,"

Project Number 38768-EG, sponsored by the Army Research Office under the supervision of Dr. Gary Anderson. The section numbering in this report conforms to the standard numbering described in **ARO FORM 18**, November 2000 Edition. As noted in ARO FORM 18, parts (1) Foreward, (2) Table of Contents and (3) List of Appendixes are not required for this document.

(4) Statement of Problem Studied

In this research program, the investigators have sought to derive, develop and validate modeling and simulation of nonlinear dynamical systems associated with military ground vehicles. One of the primary goals of the research has been to reduce model preparation time for producing accurate, stable simulations of military ground vehicle performance. Moreover, it has also been an aim of the research to reduce model simulation time for military ground vehicles to enable virtual prototyping of nonlinear vehicle dynamics.

The research has investigated the use of Lie algebraic methodologies for stabilizing constraints in redundant multibody models with a large number of degrees of freedom. In this formulation, updated dynamics and constraint force corrections are estimated iteratively, and independently, using augmented Lagrangian methods. The proposed framework can be used to derive a priori estimates on constraint violation, and hence stability. Adaptive stabilization techniques that are dependent on the required fidelity of the model simulation are employed to enforce constraints. In contrast to recursive order N formulations for collections of bodies connected in a topological tree, the formulation is amenable to Order N formulations expressed in terms of redundant coordinates.

(5) Summary of Important Results

During the period January 1 1998 through December 31 1998, a theory for utilizing Lie Algebraic formulations to enable constraint stabilization, and thereby enable inherently parallelizable formulations of nonlinear multibody dynamics was derived and validated in prototypical simulations. The technical content of the formulations was accepted for publication in two prestigious peer-reviewed journals, *Philosophical Transactions, Royal Society of London A and Nonlinear Dynamics*. The principal investigator visited Picatinny Arsenal and initiated collaborations with Michael Mattice to develop nonlinear simulation and experimental verification in the context of virtual prototyping. Preliminary designs for an experimental testbed to simulate nonlinear dynamics of vehicle mounted, rapid-retargetting weapons platforms were developed. Similar efforts were made with Redstone Arsenal, through Dr. Mike Hale. Their HUMV model was modified to incorporate a rapid retargeting weapon platform to evaluate nonlinear MBD control methodologies and experimental design. Numerical simulation and tests were very promising.

During the period January 1, 1999 through December 31, 1999, further technical refinements were made of a methodology for constraint stabilization via Lie Algebraic control methods.

Numerical studies of the performance of the constraint stabilization method were carried out for a coupled system comprised of the HMMWV and weapon platform subsystem. In addition, modal scheduling methods were developed to obtain reduced order models of structural flexibility. The stability of these methods was derived by employing hybrid system theory.

During the period January 1, 2000 through December 31, 2000, the research team disseminated technical developments derived during the past year at the 41st *AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference.* In two distinct presentations entitled (1) "Constraint Stabilization in Nonlinear Dynamics Via Control Theoretic Methods," *AIAA Paper 2000-1752*, and
(2) "Modal Scheduling and Switching Systems," *AIAA Paper 2000-1412*, the research team presented methods for continued development of a theory for reduced order models of flexible components in multibody vehicles. In addition, the research program graduated its first PhD candidate during the reporting period. Dr. Dwayne McDaniel graduated with his PhD and was responsible for much of the coding of the modifications to the HMMWV vehicle to accommodate a flexible subsystem. In addition, Dr. McDaniel implemented and tested the initial modal scheduling benchmark cases. It should be emphasized that the implementation of effective modal scheduling methods for dynamic simulation relied on the development of modal error estimators. Thus, a central achievement of the past year was the derivation, development, implementation and testing of modal error estimators. Recall that the methodology developed within this research effort employs an adaptive mode switching technique. In this formulation, a very small number of component modes are adaptively selected from a highly redundant dictionary of component modes. Preliminary computational and numerical experiments indicate that the method is very promising for obtaining accurate, low dimensional models of system dynamics. From a technical standpoint, the research established conditions that guarantees that the modal selection process yields a stable numerical scheme.

(6) Listing of Publications

(a) Papers Published in Peer-Reviewed Journals

(1) Kurdila, A.J., Webb, G., Fitz-Coy, N. and McDaniel, D., "Lie Algebraic Control for the Stabilization of Nonlinear System Dynamics Simulation," *Nonlinear Dynamics*, Volume 20, pp. 55-84, 1999.

(2) Junkins, J.L, Akella, M.R., Kurdila, A.J., "Adaptive realization of desired constraint stabilization dynamics in the control of multibody systems," *Philosophical Transactions: Mathematical, Physical & Engineering Sciences*, Volume: 359, Number: 1788 Page: 2231 – 2249.

(b) Papers Published in Non-Peer-Reviewed Journals

None

(c) Papers Presented at Meetings

(1) D. McDaniel, N. Fitz-Coy, A. Kurdila (Florida, Univ., Gainesville), and M. Hale (U.S. Army, Redstone Technical Test Center, Redstone Arsenal, AL), "Constraint Stabilization in Nonlinear Dynamics Via Control Theoretic Methods," *AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference* and Exhibit, 41st, Atlanta, GA, Apr. 3-6, 2000, *AIAA Paper 2000-1752.*

(2) D. McDaniel, A. Kurdila, and N. Fitz-Coy (Florida, Univ., Gainesville), "Modal Scheduling and Switching Systems," *AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference and Exhibit*, 41st, Atlanta, GA, Apr. 3-6, 2000, *AIAA Paper 2000-1412*

(d) Manuscripts Submitted, but not published

None

(e) Technical Reports Submitted to ARO

None

(7) Participating Scientific Personnel

PI:	Andrew J. Kurdila
Co-PI:	Norman Fitz-Coy
Students:	Dwayne McDaniel (PhD conferred, 2000)
	Jianzhu Liu (MS Student, degree conferred, 2001)
	Jason Harper (MS Student, degree conferred, 2001)

(8) Report of Inventions

None

(9) Bibliography

None

(10) Appendixes

None